Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Procedia - Social and Behavioral Sciences 111 (2014) 869 – 879

Procedia
Social and Behavioral Sciences

EWGT2013 – 16th Meeting of the EURO Working Group on Transportation

A web based application for urban transport infrastructure planning for delivering hydrogen

Jesús Gallego[a], Beatriz Royo[a], Emilio Larrodé[a,]*

[a]*University of Zaragoza, María de Luna s/n, Zaragoza, 50.018, Spain*

Abstract

The appearance of new alternative fuels for urban fleets has motivated the developing of a new methodology to plan the fuel supply infrastructure required to cover the new demand. The fuel cell hydrogen vehicle has been identified as the alternative with the greatest possibilities in the medium to long term to replace conventional vehicles.
In order to make easier and cheaper the implantation of the new supply infrastructures, it is necessary to develop analyses which allow us to determine the design, size and so on. This research shows an analysis and a tool which allow us to approximate the design and size of a new hydrogen distribution infrastructure.
To calculate the parameters needed to introduce in the infrastructure, the number of vehicles, the hydrogen consumption of these vehicles and the technology utilized to supply the hydrogen are taken into account. One of the most important considerations to determine these parameters is the hydrogen delivery system that is going to be used for the hydrogen fuelling stations.
With the objective of validate this tool, a case study has been defined. This case is based on the implementation of a tram line powered by hydrogen. It is also defined, the requirement regarding to the necessities and the hydrogen supply infrastructure.
The most important variables are the cost, demand, location of facilities and security of supply.
Due to the big amount of parameters and variables this tool could be a good decision support system to help to delimit the size, cost, design…of this particular kind of infrastructure.

Keywords: Hydrogen infrastructure; hydrogen station; transport; facility sizing; planning ;

* Jesús Gallego, Beatriz Royo, Emilio Larrodé. Tel.: +34 976 761 888; fax: +34 976 762 670.
E-mail address: jgallego@unizar.es, elarrode@unizar.es, broyoa@unizar.es

1877-0428 © 2013 The Authors. Published by Elsevier Ltd.
Selection and/or peer-review under responsibility of Scientific Committee
doi:10.1016/j.sbspro.2014.01.121

1. Introduction

The transportation system provides basic social functions, but under present conditions cannot be considered as a sustainable system. Transportation, partly motivated by economic growth of certain countries with a high potential like China, India or Brazil (Chaitanya, 2007), is responsible for 20% of the expected increase in world energy demand and emissions of greenhouse gases until the year 2030. In parallel the economic problem motivated by the end of cheap fossil fuels should be faced. According to experts, peak production of fossil fuels already passed (Tsoskounoglou, Ayerides, & Tritopoulou, 2008).

The transportation sector is one of the main consumers of primary energy worldwide. This sector represents approximately 18% of primary energy consumption and 17% of global CO2 emissions, and road transportation is the largest responsible for them. Therefore, one of the keys to achieving a clean environment and fight against climate change is to reach an emission-free transportation system.

In this sense, the electric vehicle complies with zero emissions condition. Among the different electrical systems, we have identified the hydrogen fuel cell vehicle as the alternative with a greatest potential in the medium to long term to replace traditional vehicles. Hydrogen, the most abundant element on the planet, can be used as a clean and efficient fuel, achieving performance comparable to that provided by conventional fossil fuels. In the last years has been performed a large research in order to incorporate the hydrogen to the transportation sector, particularly for medium and long distance (Andrews & Shabani, 2012). Hydrogen is a clean energy carrier and when it is used cause a positive impact on climate change, local air quality and noise pollution (Doll & Wietschel, 2008; Balla & Wietschel, 2009).

It is expected that in 10-20 years (McKinsey, 2010), the number of hydrogen vehicles will increase significantly, from the early years, in which the demand will be low and predominantly intended for captive and demonstration fleets, to the point in which all consumers will use this type of vehicle.

Nowadays, any well-defined optimization criterion is followed in order to locate these facilities. Because they are used by localized fleets, hydrogen station location follows proximity criteria, and in many cases these facilities are private. This study is motivated by the necessity to develop a methodology that allows the parameterization of the "fuel" supply infrastructure needed by new powertrain concepts in a transportation system based on electric cars. In this situation, the necessity to create a tool helping to solve the sizing of hydrogen refuelling stations and their related logistics is propounded. This tool is conceived under certain conditions of operation, accessibility, availability and feasibility. In order to implement in an urban environment a clean transportation system based on hydrogen, the required hydrogen infrastructure should be technically and economically evaluated from the developed methodology.

The development of this methodology is going to help sizing hydrogen refuelling stations in the most efficient way as possible. This methodology takes into account the demand in the different times of deployment. Find the optimal location, based on both logistical and technical criteria, is really important because of the high building cost of this kind of facilities. In conclusion, is going to be provided a solution that can be considered as a tool to assist decision making for those who manage these facilities.

There are studies that have attempted to respond the problems described in this article, but has not been identified any methodology that would solve the global problem. For example, there are models that analyze different alternatives for production, storage and distribution of hydrogen and are able to calculate the infrastructure and hydrogen transport system capital costs (Ogden, 1999), and there are other studies in which production and distribution systems are analyzed and qualitatively compared for different scenarios based on demand and the time period (Markert, Nielsen, Paulsen, et al., 2007).

Nomenclature

λ	Weight based on the cost; it is associated with the technological options in the developed tool
λ_η	Weight based on the efficiency; it is associated with the considered technological options in the developed tool
R	Value based on cost, from 1 to n, associated with each of the considered technological options in the developed tool
R_η	Value based on efficiency, from 1 to n, associated with each of the considered technological options in the developed tool
R_T	Sum of the values associated with each of the considered technological options in the developed tool
C_{fuel}	Fuel costs
C_{eq}	Cost of the required equipment
C_{ener}	Energy costs
$C_{sup.\ H2}$	Cost of the external hydrogen supply system
η_{procs}	Efficiency of processes that normally happen in the operation of a hydrogen station
$\eta_{sup\ H2}$	Hydrogen supply system efficiency

2. Methodology

In order to define the needs of the hydrogen supply infrastructure, a methodology has been proposed. This methodology became a tool to assist decision making and to evaluate different possible solutions under technical and economical criteria. To evaluate the possibilities, it considers known parameters as: travel routes, distances of these routes, planned frequencies to be performed and the number of vehicles travelling each route and the estimated refuelling time. The suggested methodology follows the next process:

- Full database: it contains many models of the different equipments depending on the kind of station, their technical data, the estimated cost and etc.
- Determination and simulation of routes.
- Modeling of vehicles.
- Input parameters definition: operating times because affect to the total refuelling time, filling percentage of vehicle tanks and number of hydrogen dispensers per station. These data are required to determine the number of hydrogen dispensers needed to cover the total demand for hydrogen.
- The number of hydrogen stations and the number of hydrogen dispensers must be calculated to cover expected hydrogen demand. The hydrogen can be in different states and pressures, so this factor must be taken into account to determine the number.
- Selection of the technologies to be analyzed as potential for future installations. It considers the type of hydrogen demand to be covered: state and pressure.
- Combination of the considered technological options.

2.1. Optimization and sizing tool

According to this methodology has been developed a web application. This application helps to determine the required hydrogen supply infrastructure in order to satisfy the necessities. The general scheme of this web tool is described in Fig 1.

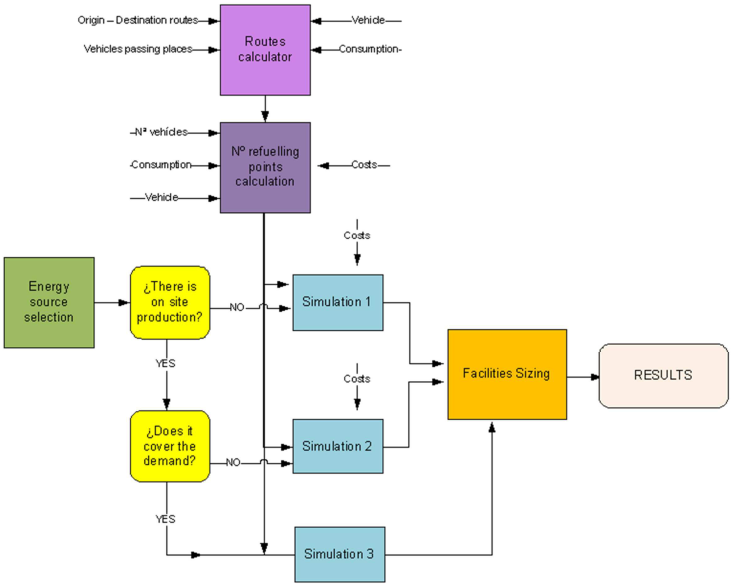


Fig. 1. General outline of the calculation tool

Google Maps API functionalities have been integrated in the web tool Fig 2. In this way, the simulation and route defining tasks are easier and intuitive. A precise definition of both, the routes and the fleet of vehicles that will use the facilities, will help to get a more optimal solution. The results of applying the cost selection are shown in the Fig 3.

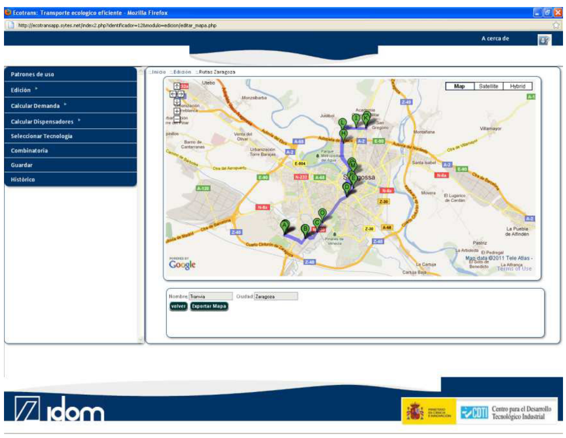
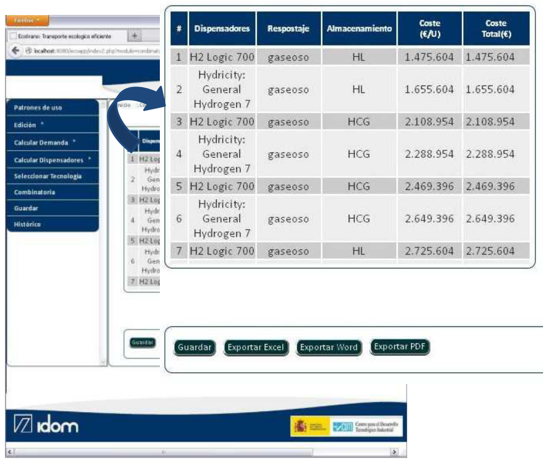


Fig. 2. Route Simulation Screen;



#	Dispensadores	Respostaje	Almacenamiento	Coste (€/U)	Coste Total(€)
1	H2 Logic 700	gaseoso	HL	1.475.604	1.475.604
2	Hydricity: General Hydrogen 7	gaseoso	HL	1.655.604	1.655.604
3	H2 Logic 700	gaseoso	HCG	2.108.954	2.108.954
4	Hydricity: General Hydrogen 7	gaseoso	HCG	2.288.954	2.288.954
5	H2 Logic 700	gaseoso	HCG	2.469.396	2.469.396
6	Hydricity: General Hydrogen 7	gaseoso	HCG	2.649.396	2.649.396
7	H2 Logic 700	gaseoso	HL	2.725.604	2.725.604

Fig. 3. Results applying the cost selection criteria

The implementation of this model comprises a calculation algorithm that determines the best possible technological combination in a short time. This algorithm allows reducing the search space in case of there being a big number of combinations.

As from data regarding the hydrogen demand and the delivery times specified in the database, the required number of hydrogen dispensers can be calculated for a first step in the hydrogen station sizing. With this data (number of potential hydrogen dispensers), available technologies (electrolysis production, reforming, supply by pipe and supply by tanker) and economic and performance data, all possible combinations would be considered and choose the best solution.

2.2. Tool Optimization Criteria

Prior step to the final result provided by the tool, costs and energy efficiencies are calculated as criteria for analyzing the different technology options and determine the optimum. It will consider: supply (water, energy, gas or hydrogen), production, hydrogen storage and delivery.

A value (R and $R\eta$ for cost and efficiency respectively) will be associated to each of the options. These variables take value from 1 to n, where n is the number of possibilities that are take into account. Value n is associated to the best option, whereas the worst take the value 1.

In order to obtain a result which takes into account both criteria, associated values to each option are added, each one multiplied by a weight (λ , λ_η). These weights will take different value depending on whether exists a preference by efficiency or cost criteria. The option with a higher R_T is the optimum.

$$OPTIMAL\ CHOICE = MAX\ (R_T) \tag{1}$$

Where:

$$R_T = (R_€\ x\ \lambda_€) + (R_\eta\ x\ \lambda_\eta) \tag{2}$$

λ and λ_η, take values from 0 to 1 depending on the importance, further must satisfy the next condition:

$$\lambda_€ + \lambda_\eta = 1 \tag{3}$$

The selection criteria based on cost is defined by the following function:

$$f\ MIN\ COST\ (C_{fuel} + C_{eq} + C_{ener} + C_{sup\,H2}) \tag{4}$$

The selection criteria based on efficiency meets the following function:

$$f\ MAX\ EFFICIENCY\ (\eta_{prod}\ x\ \eta_{procs}\ x\ \eta_{sup\,H2}) \tag{5}$$

Table 1 lists the efficiency of major processes referred to equation 5, whose values correspond to the most representative percentages extracted from different sources (Haman & Stiever, 2007; Wang & Mintz, 2003; IEA Energy Technology Essentials, 2007).

Table 1. Efficiency of the different processes

PROCESS	EFFICIENCY %
Stream reforming (natural gas)	80
Electrolysis	35*
Liquefaction	55-70
Gasification	70
Compression	90
Pipe transport	80

Cryogenic tank transport	85
Tube trailer transport	85

3. Methodology

To develop the software application which manages the calculations and decision processes, the next activities have been developed.

- Application design. As it is a central management system, it has been designed a database to store the high quantity of information and a web application to take control of data support and to display the results of the calculation process.
- As database management is used MySQL, which is an open source database, and to develop the web application PHP, a server-side scripting language. The calculation program was developed in C++ because it is a powerful language. The link between the web application and the calculation program is through the use of a variable which launches the program when is activated and shows the results when is deactivated.
- Data dictionary definition. This dictionary has the objective of facilitate the location of the different variables and their meaning.
- Database definition. This database collects the technical specifications of that equipment which is available in a hydrogen refuelling station or in a hydrogen production station; or on the other hand, the estimated costs of all the considered inputs.

4. Results

With the objective of validate this methodology, a study case has been defined. This case is based on the implementation of a tram line powered by hydrogen in the city of Zaragoza. First of all, requirement and necessities are defined and later, the hydrogen supply infrastructure is calculated.

This case is supported by some authors whose works are based on the use of hydrogen and fuel cell as train and tram power system. For example, Haseli et ál. 2008, performed a CO2 emission analysis in which is evaluated the possibility of utilize a train powered by hydrogen in Ontario, Canada. These results are broaden and economically analyzed in Marin et ál. 2010. Meanwhile, Okawa et ál. 2009 have developed a train powered by a fuel cell Ion-Lithium battery power hybrid system which has efficiency higher than 50%. Nevertheless, there are previous studies focalized in the development of a train system based on the hydrogen technologies. In 1984, Steinberg&Scott made a comparison between locomotives powered by different alternative fuels, as hydrogen, versus diesel-electric conventional ones. Since then, a lot of studies regarding hydrogen systems and railway have been published: Jones et ál. 1985, Scott et ál 1993, Hillmansen 2003 and Miller et ál. 2007, among other.

For the specific case of urban trams, in Torreglosa et ál 2011, first has been developed a PEM fuel cell and Ni-metal hydride battery hybrid system and later has been evaluated the tram behavior when operates in its real world working cycle, achieving positive results regarding hydrogen consumption, efficiency and performance.

In order to define this case, are necessary the data which characterize the route and the frequency and number of trams in operation in the particular case of the tram from Zaragoza.

The modeling of the vehicle is obtained from the performance and features of the vehicle utilized at the present:

- Estimated hydrogen consumption: 0.24 kgH2/km
- Number of fuel tanks: 6
- Storage pressure: 700 bar
- On board hydrogen storage capacity: 28 kgH2

In order to calculate the diary hydrogen demand, the most adverse option regarding the scheduled frequencies and route are considered. According to the values relating to the on board hydrogen storage, total travel distance and the estimated hydrogen consumption, the maxima number of complete rounds without refuelling are four.

Also is necessary to know the period of time required for refuelling the trams ($T_{refuelling}$), depending on the number of complete rounds: one, two, three or four, until the last refuelling activity.

Table 2. Refuelling time depending on the number of rounds

	No Rounds			
	1	2	3	4
$T_{refuelling}$ (min)	10	18	26	33
$T_{appoach}$ (min)	0.5	0.5	0.5	0.5
$T_{preparation}$ (min)	1	1	1	1
$T_{leaving}$ (min)	0.5	0.5	0.5	0.5
T_{supply} (min)	7.686	15.372	23.058	30.743

From frequency data, refuelling times showed in Table 2, and knowing that 90 minutes per complete round are required, the diary refuelling timetable is obtained.

In this particular case, the obtained refuelling timetable requires the installation of two hydrogen dispensers with the aim of responding to the calculated hydrogen demand (with only one dispenser is not possible to meet the demand). Therefore, for the 18 trams that are scheduled to work daily, the average number of rounds is 9.1111 (164 rounds in total according to the most restrictive refuelling timetable / 18 vehicles).

Among the all the possibilities, the technologies to be taken into account to be included in the refuelling facility are selected. The options to be selected are:

- Refuelling system: liquid or gaseous. It is limited by type of vehicle.
- Hydrogen storage: liquid (HL) or compressed gaseous (HCG)
- Hydrogen supply:
  - outer: liquid or gaseous
  - in situ hydrogen production by reforming
  - in situ hydrogen production by electrolysis
  - combination of some of these supply systems

As in this case of validation the on board hydrogen storage system available in each tram is based on hydrogen compressed gas (HCG) tanks, It is only is necessary to refuel in gaseous state, so only gaseous refuelling and gaseous storage have been selected as possible in the future hydrogen refuelling station. The change of state from liquid to gas makes to lose energy and it means efficiency and economic losses. In this way, the study is delimited to 6 options that are summarized in Table 3.

Table 3. Options that are considered in order to configure the hydrogen refuelling station

Option	State in the refuelling system	State in the storage system	Supply system
1	Gaseous	HCG	Outer gaseous hydrogen supply + Reforming
2	Gaseous	HCG	Outer gaseous hydrogen supply + In situ production by electrolysis
3	Gaseous	HCG	In situ production by electrolysis + reforming

4	Gaseous	HCG	Outer gaseous hydrogen supply
5	Gaseous	HCG	Reforming
6	Gaseous	HCG	In situ production by electrolysis

Finally, according to the previous restrictions, is determined that the optimal configuration of the station comprises a 700 bar hydrogen refuelling station with two hydrogen dispensers. Next table summarizes the different equipment configuration results for each of the six considered options:

Table 4. Equipment required depending on the considered options

Option 1	Model	No
Purifier	Purif (500kg)	1
Compressor	H2logic 1-1000 BAR DIAPHRAGM O	2
HCG Tank	H2G 350 (2,000kg)	1
Reformer	HyGear 200	1

Option 2	Model	No
Pre-treatment	HGenerators Water distiller 1	2
Electrolyser	Alkaline electrolyser 120.0	2
Purificator	Purif (500kg)	1
Compressor	H2logic 1-1000 BAR DIAPHRAGM O	2
HCG Tank	H2G 350 (2,000kg)	1

Option 3	Model	No
Pre-treatment	HGenerators Water distiller 1	1
Electrolyser	Alkaline electrolyser 510.0	1
Purificator	Purif (1,000kg)	1
Compressor	H2logic 1-1000 BAR DIAPHRAGM O	2
HCG Tank	H2G 350 (2,000kg)	1
Reformer	HyGear 250	1

Option 4	Model	No
Compressor	H2logic 1-1000 BAR DIAPHRAGM O	2
HCG Tank	H2G 350 (2,000kg)	1

Option 5	Model	No
Purificator	Purif (2,000kg)	1
Compressor	H2logic 1-1000 BAR DIAPHRAGM O	2
HCG Tank	H2G 350 (2,000kg)	1
Reformer	HyGear 250	2

Option 6	Model	No
Pre-treatment	HGenerators Water distiller 1	1
Electrolyser	Alkaline electrolyser 1175	1
Purificator	Purif (2,000kg)	1
Compressor	H2logic 1-1000 BAR DIAPHRAGM O	2
HCG Tank	H2G 350 (2,000kg)	1

Costs for the hydrogen stations, depending on the combination of the two hydrogen dispensers and the technologies considered are showed in Table 5.

Table 5. Cost of the hydrogen station.

Hydrogen pump	Option	Cost ( )
H2 Logic 700	4	733,430
Hydricity 700	4	913,430
H2 Logic 700	2	2,083,561
Hydricity 700	2	2,263,561
H2 Logic 700	1	2,734,585
Hydricity 700	1	2,914,585
H2 Logic 700	6	3,318,132
Hydricity 700	6	3,498,132
H2 Logic 700	3	6,136,580
Hydricity 700	3	6,316,580
H2 Logic 700	5	8,419,848
Hydricity 700	5	8,599,848

The results returned by the application web, refers to the number of hydrogen refuelling stations and its size (depending on the equipment and technologies that will mount), will be used as baseline data to determine the optimal location among possible.

5. Conclusions

The proposed methodology allows obtaining some initial solutions about the hydrogen infrastructure required. It allows us to know the needs of a new hydrogen-based transportation fleet. These solutions, ordered by technical and economic criteria, are helpful in the initial stage of decision making.

The incorporation of this methodology to an application web capable of housing a database with different models for the equipments and devices that are present in the different combining technologies produces results quickly; thereby, the analysis of different solutions and changes in the obtained technological combinations in order to achieve optimal solutions are easy to perform.

The expected hydrogen daily demand to be supplied by the facility is an essential input before determining the optimum size of hydrogen refuelling station. There are two possibilities in order to determine the demand:

- Hydrogen demand obtained from vehicle fleets, public or private, that will use hydrogen in a given time horizon. Estimative option depending on the number of vehicles of each type: cars, vans, buses or trucks.
- The design and study of the routes that are followed by vehicles. In the case of captive or private fleets the routes are known and it makes possible to perform more in-depth analysis of them and the estimated demands are much more close to the real ones.

While de calculation tool or application web is being designed, there are two variables to take in special consideration. These variables are the techniques and economical and their high sensitive when the hydrogen supply system is chosen for the hydrogen fuelling station. The supply system depends on four basic variables: cost, demand, location of facilities and security of supply.

Aknowledgements

The methodology presented in this work has been developed within the context of the project EcoTrans "Ecological Technologies for Urban Transport", framed within the CENIT project 2008/0712 funded by the *Centro para el Desarrollo Tecnológico Industrial* of the Spanish Ministry of Science and Technology. The consortium consisted of over 20 companies and institutions, among IDOM, and whose leader was CAF.

References

Chaitanya K. (2007). Rapid economic growth and industrialization in India, China & Brazil: at what cost? William Davidson Institute. Working Paper Nº 897.

Tsoskounoglou M, Ayerides G, & Tritopoulou E. (2008). The end of cheap oil: Current status and prospects. Energy Policy. October. Vol.36-10. p.3797–3806.

Andrews J, & Shabani B. (2012). Re-envisioning the role of hydrogen in a sustainable energy economy. International Journal of Hydrogen Energy. Vol.37-2. p.1184–1203.

Doll C, & Wietschel M. (2008). Externalities of the transport sector and the role of hydrogen in a sustainable transport vision. Energy Policy. Vol.36-11. p.4069–4078.

Balla M, &Wietschel M. (2009). The future of hydrogen-opportunities and challenges. International Journal of Hydrogen Energy. Vol. 34-2, p.615–627.

McKinsey (2010). The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles. McKinsey Report

Ogden J. (1999). Developing an infrastructure for hydrogen vehicles: a Southern California case study. International Journal of Hydrogen Energy., Vol. 24-8, p.709-730.

Markert F, Nielsen S, Paulsen J, et al. (2007). Safety aspects of future infrastructure scenarios with hydrogen refuelling stations. International Journal of Hydrogen Energy, Vol. 32-13, p.2227-2234.

Haman K, & Stiever E. (2007). Literature Review of Hydrogen Production, Storage, Distribution, and Utilization Technologies

Wang M, Mintz M. (2003). Benefits and Costs of Hydrogen Fuels, Argonne National Laboratory.

IEA Energy Technology Essentials. (2007).

Haseli Y, Naterer G.F, & Dincer I. (2008). Comparative assessment of greenhouse gas mitigation of hydrogen passenger trains. International Journal of Hydrogen Energy. Vol. 33, p.1788–1796.

Marin G.D, Naterer G.F, & Gabriel K. (2010). Rail transportation by hydrogen vs. electrification - Case study for Ontario, Canada II: Energy supply and distribution. International Journal of Hydrogen Energy. Vol. 35. p.6097–6107.

Okawa K, Yamamoto T, Hasegawa H, & Furuya T. (2009). Development of the Fuel-cell/Battery Hybrid Railway Vehicle. Railway Technical Research Institute.

Steinberg B.A., & Scott D.S. (1984). Hydrogen vs. diesel fuelled locomotives: a techno-economic appraisal. International Journal of Hydrogen Energy. Vol. 9. P.101–107.

Jones L.E, Hayward G.W, Kalyanam K.M, Rotenberg Y, Scott D.S, & Steinberg B.A. (1985). Fuel cell alternative for locomotive propulsion. International Journal of Hydrogen Energy. Vol. 10. p.505–516.

Scott D.S, Rogner H. H, & Scott M. B. (1993). Fuel cell locomotives in Canada. International Journal of Hydrogen Energy, Vol.18. p.253–263.

Hillmansen S. (2003). The application of FC technology to rail transport operations. Journal of Rail and Rapid Transit. Vol.217. p.291–308.

Miller A.R, Hess KS, Barnes D.L, & Erickson T.L. (2007). System design of a large fuel cell hybrid locomotive. Journal of Power Sources Vol.173 p.935–942.

Torreglosa J.P.Jurado F, García P,.& Fernández L.M. (2011). Hybrid fuel cell and battery tramway control based on an equivalent consumption minimization strategy. Control Engineering Practice. Vol. 19. p.1182–1194.